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TECHNICAL REPORT 4880

STATE-OF-THE-ART SURVEY FOR AUTOMATIC
OPTICAL DETECTION OF SURFACE DEFECTS
ON ORDNANCE MATERIAL



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20. ABSTRACT (Continued)

It is found in general that the ability to resolve a defect has an inverse relationship to the complexity of the background. If the background is sufficiently subdued, a simple photodetector circuit will serve. Because each defect is in a unique environment, there can be no universal solution. As the complexity of the background increases, so must the complexity of the discriminator. This is especially true when the background includes man-made objects. It can be seen that the trend is to place complex defect detection problems out of the range of cost effectiveness for low cost production items.

It is concluded that the design engineer must carefully evaluate the specific problem in order to obtain the simplest, most cost effective defect detection system that meets quality control criteria.

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INTRODUCTION

The majority of optical inspection on items for defects is done by human operators, and for good reason. The human has high resolution, his analysis is unsurpassed, and there is high confidence in the resulting decision. Yet, as sophisticated and versatile as the human can be in decision making, there are many areas where it would be highly advantageous to have an automated optical inspection system. These areas are found wherever high volume, low cost inspection requirements exist. Almost any defect that can be picked out by a human inspector can also be picked out by an automated system, if one is willing to provide unlimited time and money. If the defect has high contrast against a negligible background, the components necessary can consist of a lens, a photodetector and a voltage discriminator. As the background becomes more complex, and the defect less pronounced, resolution (detection) and classification become increasingly more difficult. Although the more difficult cases are presently being attacked only at research levels and at great expense, yet, if the volume and need justify, even complex cases can be reduced to practical levels. An example is provided by the Post Office letter reader, a system that can economically classify letters at the rate of 43,000 per hour.

The goal of this report is to provide a guide for the reader as to how far he may practically expect to proceed, using existing technology, in solving a defect recognition problem.

BACKGROUND

The art of optical detection of surface defects is the art of pattern recognition, thus this survey is organized around pattern recognition procedures.

There are several systems of logic on which pattern recognition is based (Ref 1, 2, 3). The approach most generally employed proceeds in a manner as illustrated in the following example. Assume there exists a field of view in which a target (defect) lies. For this example we have chosen a crack to represent the target against a background of random noise (Fig 1). Assume also that the information about the scene consists only of the output of a photodetector, which is proportional to the brightness of the scene. The output over a single scan is shown in Figure 2. The crack blip in Figure 2 can be readily discerned by the reader; however, getting an electronic system to perform, which to a human represents the simplest of tasks, can present a formidable problem. The ability of a machine to recognize a target is a function of the machine's ability to measure a characteristic or characteristics of that target that differentiates the target from its background. The amplitude of the crack signal can represent one such characteristic. If we examined numerous crack signals and background signals, we

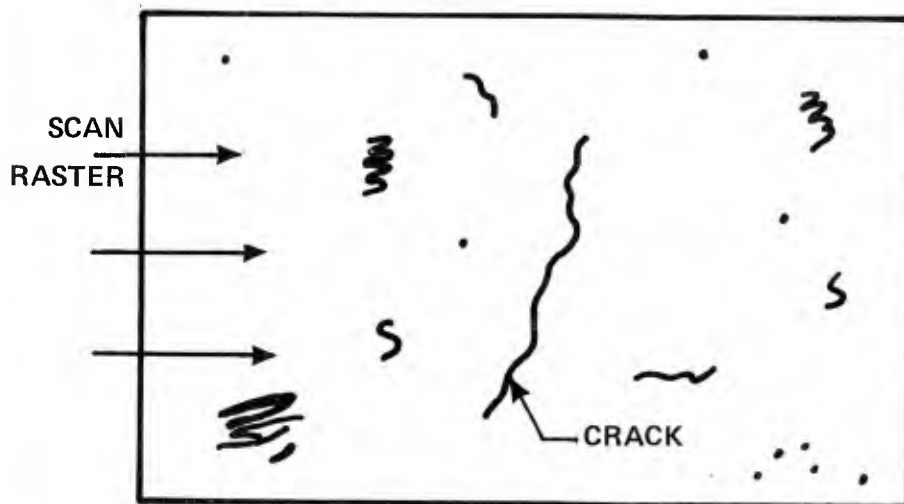


Fig 1 An example of a typical crack environment

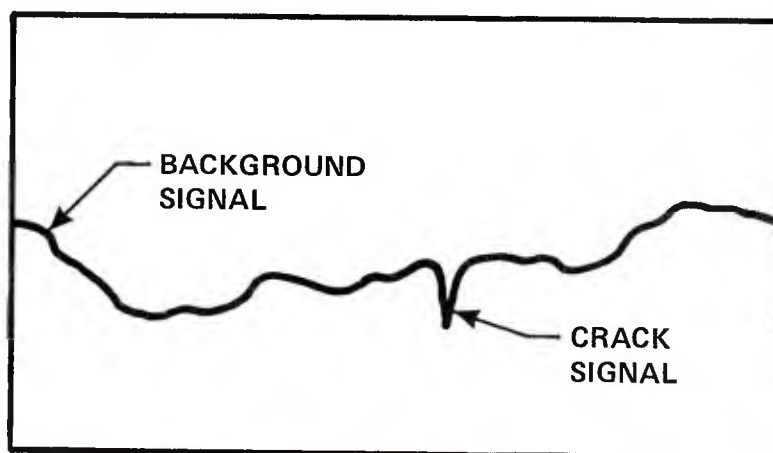


Fig 2 Photodetector output, single scan

would expect to find a distribution of amplitudes as shown in Figure 3. It can be seen that if amplitude is the sole criterion for crack identification, there exists a large region of ambiguity where signals arising from cracks and background can be confused. Notice that the crack signal, as shown, is sharper in profile than that coming from the background and thus is composed of higher electronic frequencies. If frequency now becomes a second characteristic measured, it is possible to construct a two-dimensional vector space, similar to Figure 4.

Notice how the ambiguous region has been reduced by use of the second characteristic. Further resolution can be achieved by the measurement of additional characteristics. When the resolution of the target from the background becomes adequate, analysis can stop. If not, additional characteristics must be measured until the desired resolution is achieved. This analysis can be generalized to apply to alternate sources of information, such as those arising from radar signals, magnetic measurements, etc., and can be profitably applied to include other techniques of nondestructive testing.

Bear in mind that in the preceding example, the analysis was against a random background. In numerous cases, however, discrimination will also have to be made against regularly shaped objects in the field of view, such as gears, rods, edges, or cavities. Under these conditions, measurements of more complex characteristics, such as moments, corners, or perimeters, may become necessary.

A partial list of measurable characteristics normally associated with optics would include: brightness, color, contrast, width, length, perimeter, area, corners, moments, shape correlation, and texture. Brightness can be measured with a simple photodetector circuit. Color and spectral characteristics may require several photodetectors and spectral filters. Width, length, perimeter, and area become more difficult to measure, requiring analog or digital data processing systems. Many defects may be positively identified by use of these four parameters alone. Moments and corners may require small digital computer systems. Correlations and texture measurements may require large computer memories and can be expensive and time consuming to obtain.

Because there are so many possible targets to identify against such a large variety of backgrounds using a large variety of potential characteristics that may be measured by numerous techniques, almost any real defect detection problem must have a specifically tailored solution. The design engineer must make the optimum trade-off between the convenience of measuring each characteristic, its resolution potential, and cost effectiveness.

For example, if the problem consisted of identifying dogs against a background of snakes, legness would be an ideal characteristic to measure. If there were only a few

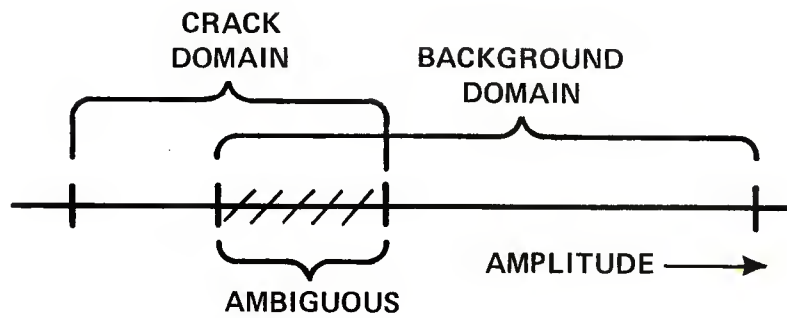


Fig 3 Amplitude domains for cracks and backgrounds, one dimension

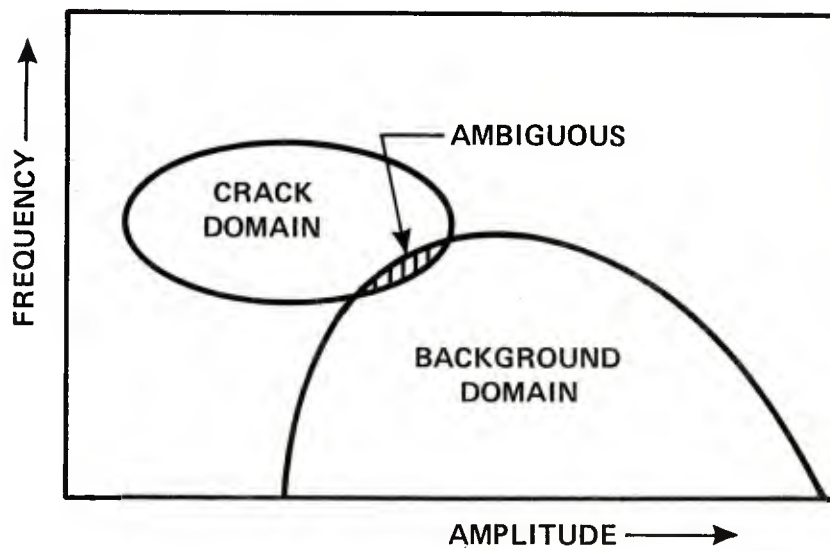


Fig 4 Amplitude frequency domains for cracks and background, two dimensions

cents available to identify dogs versus snakes per field of view, and the quality of legness required dollars per field of view to measure, legness would become an inappropriate variable. If the problem were identifying dogs versus cats, the quality of legness would again become inappropriate.

The concept of resolution for these characteristics can become difficult to define. The resolution of an electronic signal against a random background is well defined, as is resolution for points of light against a black background, but what is the definition of resolution for corners against a geometric background? What is the resolution ability of a system for identifying tanks against a background of trees, or trees and buildings? For the most part, resolution must be defined against the background found in normal usage and must be measured statistically.

In this report, an attempt has been made to place measurement techniques in order of increasing power and versatility. Unfortunately, associated with this increase are increases in expense and processing time. The total costs can vary significantly between processes and the engineer should take care to carefully define requirements before attacking a specific problem.

OPTICAL IMAGE PROCESSING TECHNIQUES

The general goal of an engineer in designing an optical inspection station is to develop a system such that, when a defective item passes through a field of view, a photodetector electronic system "sees" the defect, puts out an electronic signal, and the item is rejected. To ease the task of the electronic system there are steps that may be taken with the image prior to its being converted to an electronic signal. In certain cases, this processing alone, along with a photodetector circuit, will adequately resolve the defect.

Color

A defect may be detected if its color differs significantly from the background. If the color is pronounced, a single color filter-photodetector combination may prove adequate. A three filter detector system can give color resolution approaching that of the eye. A light loss is suffered in using filters and, if ambient light is low, faster response times must be traded for sensitivity. For well illuminated subjects the response time is that of the photodetector-electronic circuitry which can be designed to be more than adequate to handle mechanically handled parts. The exact response time is a function of the illumination available, field of view, band pass of the optical filter, and the detector sensitivity.

By use of diffraction gratings and self-scanned photodiode arrays, existing commercial systems can monitor up to 500 optical wavelengths simultaneously.

Reticles

Proper selection of reticles can provide a good, convenient method of making a target stand out from its background. In its simplest form, the technique can consist of matching a photodetector's field of view to the dimension of the target. This will provide maximum response from the photodetector as the target passes through the field of view. If the shape of the field of view exactly matches that of the target, the maximum photodetector response will follow. However, exact shape matching will make the output drop significantly with variations in target size and orientation. An example can be seen in considering the detection of a crack. If the field of view exactly matches the geometry of one particular crack, the minimum background light will reach the photodetector when the crack is out of the field of view, and maximum signal as the crack occupies the entire field of view and the maximum signal-to-noise ratio will follow. If a smaller crack should be found in the field of view, the S/N ratio will decrease. It can be seen that any variation in geometry or orientation of the crack will drastically reduce the S/N ratio. To obtain optimum S/N ratios, the engineer must statistically match the field of view to the family of defects to be encountered.

The field of view may be continuously swept with a linear grid pattern. If the width of the grids matches the dimensions of the target, a maximum a. c. signal will be produced, yielding size discrimination (Fig 5). If the target has a large length-to-width ratio, it can be seen that the a. c. envelope will vary depending on the orientation of the target to the grid, providing a crude form of shape discrimination.

More sophisticated variations in the scanning grid will in addition frequency modulate the target signal and provide information as to the target location in the field of view (Ref 4).

Diffraction (Ref 5)

The diffraction pattern of an object's profile may be formed by back illuminating the object with coherent light (laser) and observing the shadow formed at a distance (Fig 6). The Fraunhofer diffraction pattern (far field) for the object is formed at the focal length of a lens placed in this shadow. The dimensions of objects may be computed by monitoring the spacing of nulls in either far or near field patterns. The advantage of this technique lies in the inverse relationship between null spacing and object dimension, making rapid, accurate size measurements possible for small items. Usually this technique is used for monitoring hole sizes, slit widths, wires, or small particles. By use of

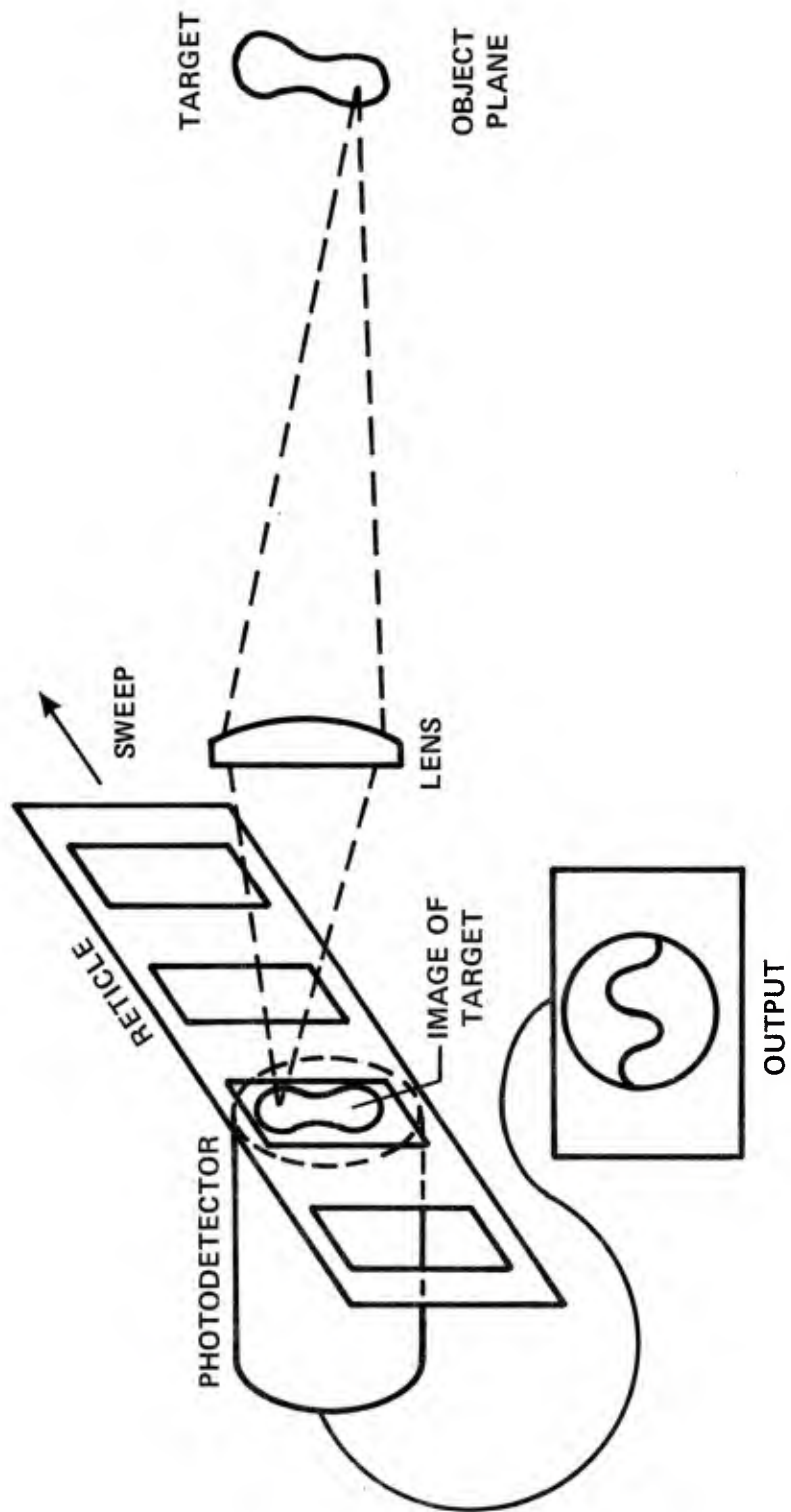
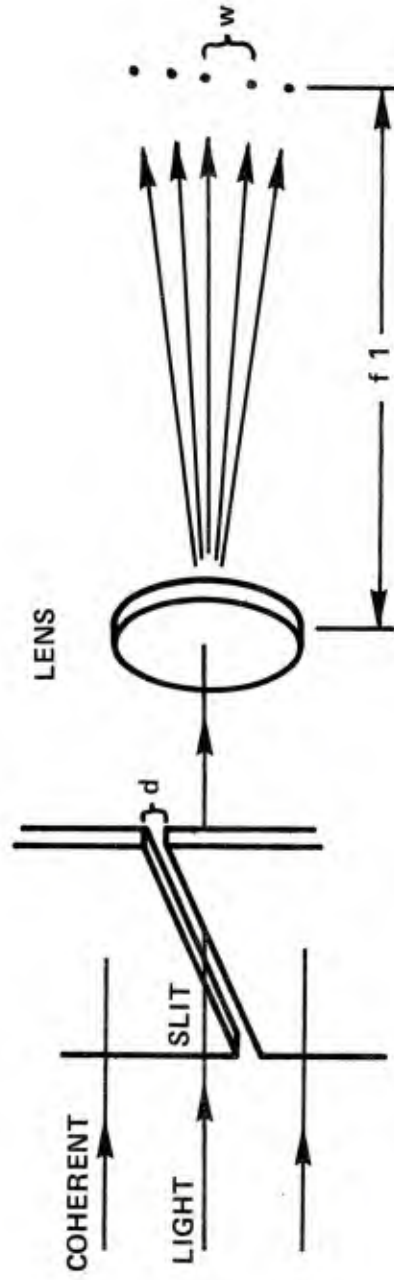


Fig 5 Simple reticle chopping system



The slit width may be computed by measuring the spacing (w) in the diffraction pattern and using the relationship $w = \frac{\lambda}{d} \times (f_1)$ where λ = wavelength of the incident radiation.

Fig 6 Example of diffraction

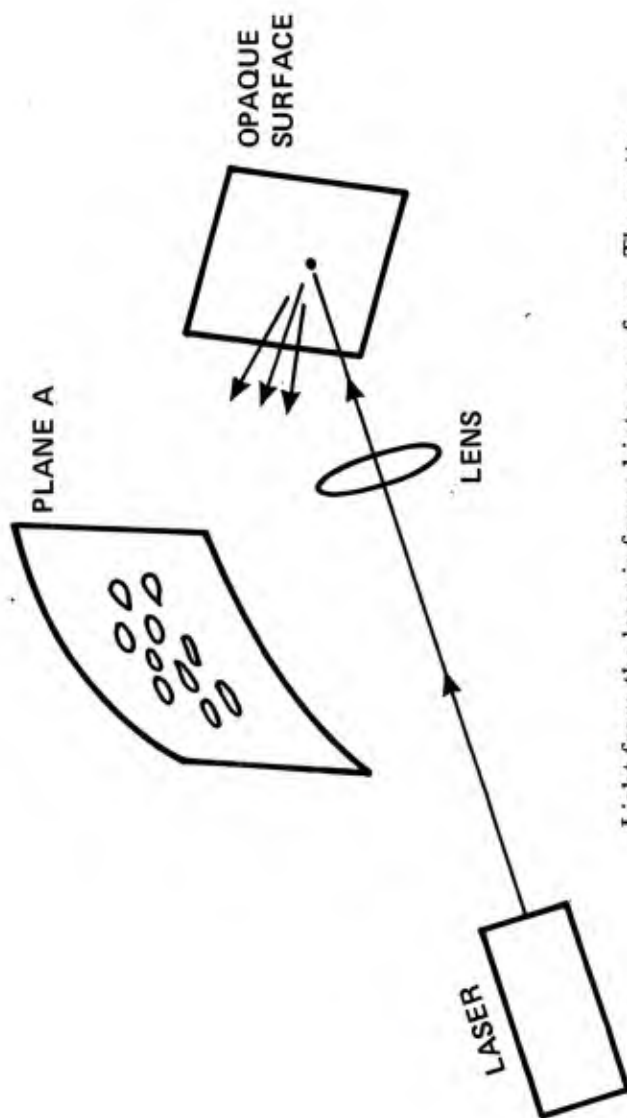
straight edges, variations in profile of flat surfaces can be monitored. On commercial equipment, accuracy from 1 to 3% of reading, and resolution to 250 microns is reported. Measurable slit widths usually range between .015 and 1.5 mm (Ref 6) and aperture diameters between .025 and .4 mm.

Scatter

In focusing a laser beam onto a surface, light is scattered in a pattern characteristic of the texture of the illuminated area (Fig 7). Since defects will alter this scatter significantly, by monitoring the pattern the presence of the defect will become evident. Unfortunately, variations normally found in the surface finish, such as scratches, polish marks, or water spots, can have a pronounced effect on the scatter and can cause false rejection of good items. The main limitation of this type inspection is in having too much sensitivity. Detection of scratches or cracks becomes difficult on surfaces having roughness values above .05 micrometer r.m.s. The effect of more diffuse surfaces may be reduced by oblique angle illumination (Ref 7). Useful focused beam diameters run down to typically 0.125 mm, with which detection of defects of .025 mm is claimed. It can be seen that numerous scans, using a beam of this diameter, are necessary to completely cover most surfaces. Systems capable of scanning 6.5-inch cylinders in two seconds have been developed. The quality of surface finishes may be monitored by these techniques (Ref 8, 9). Battelle Northwest has developed an inspection station for Frankford Arsenal that inspects 1200 small caliber cartridges per minute. It is reported that the surface of rolled or sheet metal can be continuously monitored for scratches, cracks, slivers, roll marks, or dirt pits with satisfactory results (Ref 10).

Optical Spatial Filters

By use of a relatively simple optical system, it is possible to obtain two-dimensional Fourier transformations of an object/scene (Ref 11). The basic system is made by placing two lenses of equal focal length at a distance equal to twice their focal length apart (Fig 8). This gives a one-to-one imaging system for an object placed one focal length in front of the first lens. When an object is back illuminated, using coherent light from a laser, a light distribution proportional to the Fourier transform for the object will be formed halfway between the two lenses. The properties of Fourier transforms are such that they represent the two-dimensional spatial frequency spectrum of the object, and, by proper analysis, information as to the nature of the object can be obtained (Ref 12). In this system, Fourier transforms are formed in real time and with high spatial resolution. The resolution is that of the optics used. To perform similar transformations, digital computers require large memories and long run times, and then sacrifice resolution. Periodic objects, as found in man-made structures, produce the



Light from the laser is formed into a surface. The scatter pattern produced at Plane A is characteristic of the illuminated area

Fig 7 Laser scatter

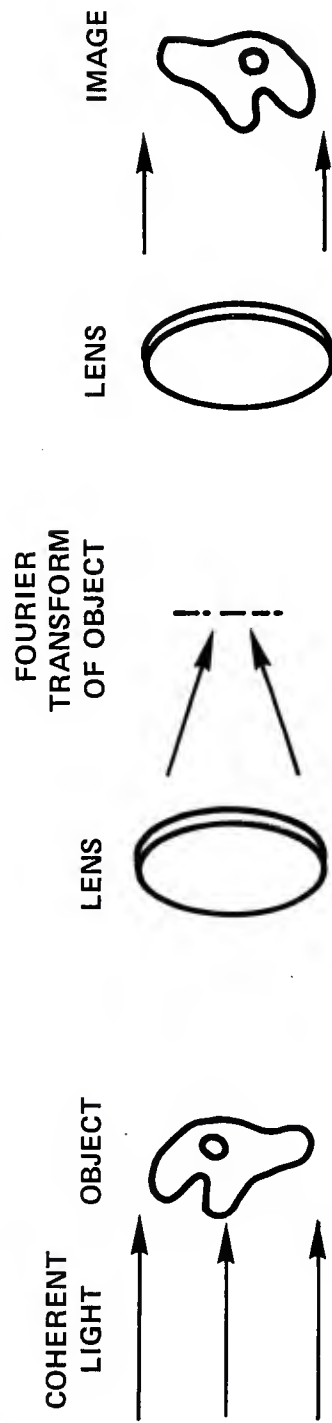


Fig 8 Optical setup for producing Fourier transforms

most distinctive patterns. This property is commonly used in classifying aerial photographs. In general, optical Fourier transform analysis works best on small objects, on the order of millimeters or less, due to the inverse relationship found between transform and object dimensions.

By monitoring the transform itself with photodetectors, objects may be classified by distinctive spatial frequency characteristics. Potential uses include land classification, fingerprint preprocessing, and particle size analysis (Ref 12, 14, 15). Special photodiode arrays integrated into minicomputers are available specifically for transform analysis. Also available are TV-monitored Fourier transform systems for manual analysis.

By placing optical filters in the Fourier transform plane, the image may either be differentiated, edge enhanced, or may have selected spatial frequencies suppressed (Ref 16, 17). Under edge enhancement or differentiation (Ref 18), the object's perimeter in the image appears as a thin, glowing line. This process has been used for radiographs (Ref 19). By use in conjunction with a simple photodetector, edge enhancement could find use in automatic perimeter measurement or as part of a system to discriminate objects with unique perimeter-to-area ratios, perhaps to signal incorrect geometries found among production items. Preferential edge enhancement, where edges lying only in a selected orientation are enhanced, has potential use in detecting misaligned components.

By the use of appropriate filters in the Fourier transform plane, selected spatial frequencies can be removed from the image. Frequency filtering can be used to improve the contrast between the target and its background where either the target or its background consists of a predominant spatial frequency. Photographs are frequently enhanced in this manner.

These operations are limited to subjects of such dimensions that they can be evenly illuminated by parallel light, usually on the order of a few inches or less. The subject must be opaque or in the form of a transparency without excessive background detail. Dust present in the system will reduce effectiveness and, as is true of most coherent optical systems, the image suffers from speckle (Ref 20).

By holographic procedures at the Fourier transform plane, filters may be constructed that are phase and amplitude matched to a specific object (Ref 21, 22, 23, 24, 25). Information transmitted to the image plane will be inversely proportional to the similarity of new objects and the original object used in producing the filter. A pattern recognition system can be made by placing a photodetector at the image plane. These type filters have become known as "Vander Lugt" filters.

A variation of this system will produce, off axis, a light distribution which corresponds to the two-dimensional mathematical correlation between the two objects (Ref 26). Optical correlation tends to work best on small objects, on the order of a few millimeters or less. The filters are specifically tailored for a particular object; slight variations in size or orientation degrade performance. The filters are not affected by object position in the field of view.

Image Subtraction (Ref 27)

Optical image subtraction takes advantage of the fact that a cosine grating placed across the Fourier transform plane will produce two images of an object, 180° out of phase. By careful positioning of two objects, one set of their images can be made to cancel out. Wherever dissimilarities between the two objects are found, there is incomplete cancellation, as a result of which differences become readily observable. This system is sensitive to slight misalignment. The maximum object dimension is on the order of 1/2-inch width.

In order to produce the effect, the subject must be back lit. Transparencies may be used if care is taken to insure flatness of the backing, as slight variations will introduce phase shifts that will alter the effect adversely. The two objects must be precisely registered; any deviation will show up as a difference reading.

OPTICAL SCANNERS AND DIGITIZERS (REF 30, 31)

In the techniques described above, the image processing was accomplished entirely with the use of coherent (laser) light. Such methods are largely based on the properties of diffraction and may properly be categorized as "analog optical computers". Despite their inherent simplicity, there are sufficient drawbacks (as described above) to frequently render it necessary to analyze defect-containing images with ordinary (incoherent) light. The data is then handled by electronic digital computer methods. Before this can be done, however, it is necessary to extract the information from the image by resorting to some form of image scanning. This section describes a variety of scanning techniques available today. The processing train discussed from this point on is illustrated in Figure 9.

The items must be optically scanned before electronic detection of defects can take place. The optical scan will determine the spatial and gray level resolution for the entire system. Also, total scan time can be the limiting factor for inspection rates. Because the scanning system limits the total information available for analysis, it is important that any information necessary to resolve the defect not be lost. However,

excessive information provided will be paid for in terms of scan and processing time. The engineer must determine the optimum trade-off between information, content, resolution, and flow rate in selecting the best scanning system for the problem at hand.

The basic scan element is called a pixel. A 500 x 500 array scan raster will provide 250,000 pixels. To double this spatial resolution 1000 x 1000 pixels will be necessary, implying an increase of four times the scan with a concurrent increase in processing times.

The stated gray scale resolution can be misleading for most practical applications, for at higher levels, one starts discriminating uneven lighting on the subject. For most analysis problems, it is usually unnecessary to provide more than 9 or 10 gray shade levels.

Mechanical Scanning

A mechanical scan of an item can be made by either moving a photodetector across the item, moving a photodetector across an image of the item, or moving the item through a photodetector's field of view. Although mechanical scanning provides the highest spatial resolution of any scanning system, it tends to be slow, up to 20,000 pixels per second. In using microscope lenses, resolution can approach one micron. Flatbed microdensitometers provide the ultimate in photometric and positional accuracy but tend to be too slow for most applications. Rotating drum scanners compromise accuracy for increased speed.

Because it can be difficult to maintain proper focus on the object, commercial systems are generally used only on flat objects, such as transparencies and photographs. Gray level discrimination can be up to 256 levels (8 bits), although only 45 to 105 levels may be useful, due to nonlinearities in the film (Ref 32). A typical rotating drum scanner will cover a 12.5 x 12.5 cm film using a 25-micron raster in 40 minutes. This rate may be reduced to 10 minutes by cutting spatial resolution requirements in half.

Laser Beam Scanners

A laser beam is swept linearly across the subject while a photodetector monitors the reflected light. After each sweep, the subject or beam is advanced. The laser beam may be deflected through the scan by either rotating or nodding mirror systems, or by acousto-optical deflectors.

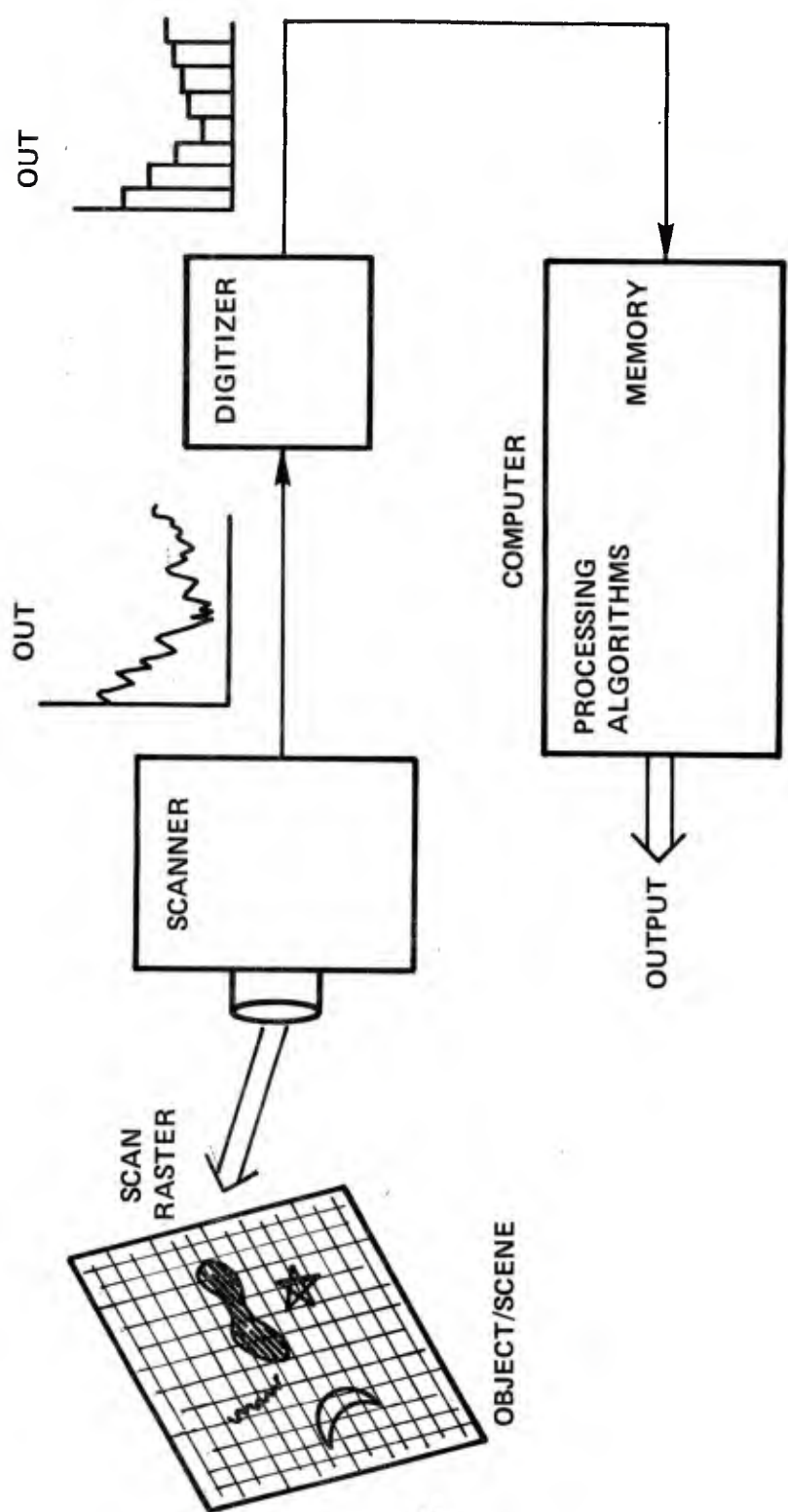


Fig 9 Basic computer image processing train

In general, laser beam scanners provide a higher signal-to-noise ratio than is found in cathode ray tube systems and thus are better on low-contrast targets. On items with curved geometries, there may be problems in holding the focus. The data rate is limited by the response rate of the photodetector, but data rates in excess of 10^6 pixels per second can be easily accomplished. Spatial resolutions can approach six micrometers. The gray level resolution is better than 64 levels.

Profilometers

The surface relief of a body can be measured to high precision by use of optical profilometers, a convenience in searching for defects with unusual depth, such as cracks or pits. They can work either by measuring variations in spot diameter on the body's surface of a focused laser beam or by measuring the variation in relative position with profile of a laser beam spot as observed at an angle. Variation in profile less than the spot diameter in extent will not be followed. Claims are made for instruments capable of measuring points down to 10 to 100 microns in extent with accuracy of 0.1 to 10 microns (Ref 28). Other reports indicate possible resolution of one nm and precision of 10 nm (Ref 29).

TV Camera Scanners

TV cameras provide analog outputs that can be conveniently processed and are extensively used in operator-computer interactive systems (Ref 34).

Spatial resolution will be described by the scan raster, conventionally 525 x 485 lines. There are systems providing up to 6000 line resolution, but unfortunately with losses in frame rate (Ref 35). By the use of lenses, the field of view can range from microscopic to stellar. The field of view is scanned effectively in 1/30 second, which is considered to be real time for human observers. Scan rates of 1/60 second are available. At present TV scanners are perhaps the most versatile scanning systems for use in image analysis. Up to 64 gray levels are resolvable, providing accuracy of 3 to 5% of true density values.

Image Dissector

The image dissector is a variation of a cathode ray tube. Its use is usually limited to applications where the subject may be well illuminated; 5 to 50 foot candles illumination is typical. Image dissector resolution can surpass 3000 TV lines per diagonal (Ref 36). Image dissectors have a high degree of positional accuracy. Up to 256 gray levels are resolvable. Processing speeds can be increased by scanning to every second,

fourth, or eighth line. Faster scan rates are penalized by loss of signal-to-noise ratio. In order to approach the S/N ratio of vidicons, the image dissector may have to run at one two-hundredth the rate of the vidicon.

When the image dissector is used in a displacement follower, at a rate of 25 KHZ, resolutions of .01% of full scale and accuracies of $\pm .51\%$ are achieved.

Flying Spot Scanner

Flying spot scanners work by imaging the focused spot of a cathode ray tube onto the subject being analyzed. Due to their low light output, sensitive detectors such as photomultiplier tubes must be used. Because flying spot scanners are based on cathode ray tubes, they have the resolution and speed generally associated with vidicon systems. Accurate imaging of the spot onto the subject requires a relatively flat subject. Geometric distortion is found at large angles. Flying spot scanners presently provide the most popular scanning method for optical character recognition work, due in part to the ability to program the spot to skip around as necessary. The systems tend to be expensive and bulky.

High-resolution cathode ray tubes are available with a spot size of .0007 inch on a 5-inch-diameter tube.

Photodiode Arrays

The concept behind this type scan is to image the field of view onto an array of photodiodes, each of which will have an output proportional to the amount of light it receives. Since these arrays have become solid state, they require less replacement than either CRT or laser scan systems. The arrays can be either linear or two dimensional, the spatial resolution being proportional to the number of photodiodes used. An advantage of these systems is that they operate at low voltage as opposed to cathode ray tube systems, which require high voltages for electron beam deflection.

Self-Scanned Arrays

Self-scanned arrays put out a sequence of pulses proportional to the amount of light received by each photodiode. Each photodiode will integrate the light received between integrations. Thus longer scan time can be traded for increased sensitivity. Scanning rates of up to 5 MHZ are available. In order to achieve the higher rates, high light levels are required. The arrays are small, 64 photodiodes typically occupying 1/8 inch in a linear configuration. Several such arrays may be placed in series to

increase linear resolution while also increasing sensitivity. Square arrays are available in a small vidicon. Signal-to-noise ratios are low, relative to that of a conventional TV camera. Monitoring systems are available with resolution to 50 microinches.

Charge-Coupled Devices (CCD)

Charge-coupled devices will probably replace conventional vidicons for TV cameras in time. Although the sensitivity of charge-coupled devices is not quite as good as that found in conventional TV, they have better precision. They have the potential to achieve the highest density of elements of any scanner. TV cameras based on CCD (100 x 100 array) with a minimum of .2 ft-candle illumination will resolve nine shades of gray, at the rate of 123 frames per second. Square arrays of up to 496 x 475 elements are being built experimentally.

ELECTRONIC IMAGE PROCESSING TECHNIQUES

Perhaps the simplest of electronic operations is obtaining a part count or checking for the presence or absence of components. A count is given every time an object blocks a light beam. For most situations, light levels may be controlled and the count may be made at regions of high detector response rates. Under these circumstances, the count rate will most likely be determined by the rate at which the items can be mechanically transported.

Width and length can be monitored by various methods, depending on the scanning system chosen. By imaging the item onto a single cell photodetector, an analog output proportional to length will be obtained. Again, fast response rates are attainable, but accuracy is sacrificed.

By imaging onto linear self-scanned photodiode arrays, the number of photodiodes illuminated will provide a digital measurement of a body's width. By use of the imaging properties of lenses, resolution down to microscopic levels may be reached. Typical scan rates will be about 2000 lines per second.

Beam scanning systems provide an output proportional to the length of time the object is scanned, hence, to its width. The resolution will correspond to the dimensions of the focused beam. Scan rates of greater than 8000 lines per second are obtainable.

After the image has been converted to an electronic signal, the signal must be properly interpreted so as to extract the target (defect) from the background.

A basic tool for analysis is the process of thresholding. That is, every point in the image is given an integer value, depending on which gray scale range it falls in, resulting in an image which is digitized. The simplest example is found when all shades of gray exceeding a preselected value are given the value of one, all others zero. This system alone, in cases where the contrast is sufficient, will uniquely identify the defect. Areas may be measured by thresholding, the area corresponding to the number of pixels meeting the threshold criterion. Unfortunately, in many cases there can be many competing objects in the field of view that are also thresholded and constitute noise from which the defect must be separated. The problem becomes more complex in that some of the "noise" represents components normally found in the item, such as gears, walls, or cavities, which are impossible to separate by any thresholding scheme.

One normally useful pre-processing step is contrast stretching, a useful enhancement technique where gray scale values tend to be bunched together and are difficult for the system to distinguish. Stretching multiplies the shade scale by a mathematical function with an eye towards stretching the contrast into a more useful range.

Preliminary to thresholding, there are analog operations that can be performed to increase the ratio of signal to random noise. Specialized equipment includes autocorrelators, signal averagers, lock-in amplifiers, and frequency filters. Mathematical operations may also be performed, such as multiplication, division, exponentiation, obtaining of sines, etc. Operations performed at this stage offer good accuracy and low cost at speeds compatible with the rate of data acquisition.

TV-Operator Interactive Systems

Commercially available TV-operator interactive systems exist that can perform sophisticated target analysis and measurement. Although TV based, they conceivably can be modified to accept any analog signal source. They are restricted in spatial resolution, gray scale resolution, and scan rates to those of the TV camera. For human analysis, they operate effectively in real time (1/30 second per frame). Gray-scale histograms are constructed and displayed in real time and serve to provide information to the operator for selection of best thresholding levels. Only a few levels are usually necessary for analysis. Various statistics on all regions falling within the selected threshold bands are computed and presented in a digital readout. Automatic measurements include area, length, width, number, and perimeters. Accessory electronics will place a cursor on objects displayed on the TV screen meeting operator selected criteria. For example, all objects with total area falling between two pre-selected values will be automatically marked. This feature can be extended to include any mathematical combination of the measurable variables, making a rather sophisticated pattern recognition unit. A running

count is maintained on the objects meeting the selection criteria, along with other statistics. With proper modifications, it would appear feasible to adapt these systems into an automated inspection station. For example, cracks display a high perimeter-to-area ratio. Automatic detection would be achieved by making and culling out all objects having regions exhibiting high perimeter-area ratios.

Other options are available. The operator can indicate an object on the screen using a light pen, and automatic measurements will be performed on the object and read out on the display. Intersects and centroids can be found. Two images can be subtracted, a useful operation where the defect can be typified in variations from a master. The image may be differentiated, providing bold outlining of objects or defects.

Pseudo-color enhancement is also available, but this type enhancement is basically an aid for human inspection.

Among presently used practical applications are automatic Petri dish analysis, automatic target tracking, and, in conjunction with a fluoroscopic screen, automatic x-ray checking of length and presence of parts (Ref 37, 38).

Considering the cost and effectiveness of present TV analysis systems, they appear to have potential to be profitably applied to many defect detection problems.

Computer Processing

By use of digital computers, a whole new range of characteristics become available to the engineer. Included are concepts such as corners, intersections, and moments. The total list becomes a function of the imagination and capability of the programmer (Ref 39). Because analysis can become lengthy and computer time is expensive, the processing rate and cost become prime considerations.

The processing cycle consists of object scan; data digitizing; input to memory; processing; output. The limiting factor in time per item will normally arise in either the data digitizing rate or in the data processing rate, while the bulk of expense will normally come from data processing.

Although these processes run very fast per bit of information, the vast quantity of information required for analysis can yield long processing times. A 500 x 500 resolution image digitized into 64 gray levels has 2,000,000 bits of information. If extensive processing is required, memory requirements can easily tax the largest of computers. Because of the large volume of information handled, processing programs can easily slip from the range of practicality.

The cost per item can be reduced dramatically by development of special purpose computers but development can be prohibitively expensive for all but very high volume tasks. An example where the expense is justified is found in post office automatic letter readers or in automatic fingerprint classifiers for the FBI.

The digitizing step can present a bottleneck for high production rates. For example, using direct feed to the computer memory, the scan digitizing rate for a TV camera drops to two frames per second.

Once the data is in the computer, mathematical operations may be performed on it. Typically, about 500,000 additive operations can be carried out per second, or 80,000 division operations. For the equivalent of TV resolution, the operations must be performed on 250,000 pixels, placing one addition, performed on each pixel of the image, in the half-second category. The process of image subtraction, with corrections for exposure differences, film non-linearities, misalignments, and geometric distortions may require 80 operations per pixel. It follows that computer image analysis can easily become impractical. Yet, Control Data Corporation has developed a computer complex that will perform this type image subtraction at the rate of 250,000 pixels per second.

The processing cost/time per image is difficult to estimate, being strongly dependent on the algorithm selected. Slight modification in the major subroutines can significantly increase the information handling rate of the computer (Ref 40). Operation rates may also be increased by parallel use of multiple computer units.

Some operations, such as Fourier transformations, require that all image data points be simultaneously stored in memory. Typical computer memories run up to 250,000 words. For TV resolution, the entire memory would be filled and allow no room for mathematical operations. In these cases resolution must be compromised.

Many operations, such as contrast stretching or local correlation, can be performed as the information feeds through, greatly reducing memory requirements and processing time. Smaller memories may be used in this case.

In some operations, where there is computer-scanner feedback, the object itself can serve as the memory. Feedback systems can be especially useful where suspect areas are to be zeroed in. TV scanners, for example, when used as memories, will have a random access time ranging from 5 microseconds to 33 milliseconds.

There are computers dedicated to specialized mathematical operations that will ease the burden of the general computer. For example, special units can be useful

where numerous repeated arithmetic operations are involved. These can perform about 10^8 additive operations per second and can have 60 ns semiconductor memories. Other systems can perform 1024 point Fast Fourier transformations in 4.5 to 60 milliseconds, or 1024 point correlations in 7 to 55 milliseconds.

Operations that are generally performed in scanner-computer complexes include contrast stretching, counts, subtraction, measurement of area, length, and width, Fourier transformation, frequency filtering, and correlation.

Software and hardware to perform analysis in related fields can be found at all levels of development (Ref 40, 41, 42). Typical are the areas of automatic classification of aerial reconnaissance photographs (Ref 43, 44), or automatic analysis of medical x-rays (Ref 45, 46, 47, 48). Many of the operations involved have potential to be profitably adapted to defect detection and an engineer's efforts can be greatly reduced by modification of existing programs or hardware to his particular problem.

In view of the general versatility and present research trends, it appears that computer image analysis will come to dominate the field of automatic defect detection in the future.

SUMMARY AND CONCLUSIONS

The ability to resolve a defect has an inverse relationship to the complexity of the background. If the background is sufficiently subdued, a simple photodiode circuit will serve. Because each defect recognition problem is in a unique environment, there can be no universal solution. As the complexity of the background increases, so must the complexity of the discriminator, especially when the background includes man-made objects. The increasing complexity necessary to solve the problem can be illustrated by image subtraction. Suppose cracks, pits, or blemishes are to be detected. By subtracting one image of an object from a second, only differences will remain and, in this case, the difference should correspond to the defect. The simplest method for subtraction is optical, but this operation is effectively limited to small transparencies. Analog TV systems will perform the subtraction in 1/30 second. However, the object must be precisely registered and lighting must be consistent from object to object. More versatile would be computer subtraction. For this case, positional and lighting variations can be compensated for, along with normal background variations; however, the increase in versatility is paid for by increased processing times.

A second illustration could be found in resolving geometric distortions in a part. If the defect consists of dimensional variations on items with simple geometry, a simple optical gauge will perform well. For small circles or spheres, monitoring the diffraction

pattern may be ideal. As the geometry becomes more complex, such as in gears, analog perimeter measurement may prove necessary and, in cases of excessive noise or background clutter, a digital analysis may have to be performed.

The preceding examples are meant to illustrate the point that the engineer needs to know the options available in order to develop the most efficient system for solving a particular defect detection problem.

In general, TV-analog analysis systems are available that perform sophisticated target identification tasks and can be adapted to solving perhaps the majority of industrial defect recognition problems. In many areas, digital computer analysis is superseding analog analysis and probably will come to dominate the field. For more difficult recognition problems, digital computers may offer the only solution.

At present, optical pattern recognition systems exist that can be applied towards solving many automatic defect recognition problems. Although offering potential to greatly improved production quality control and flow rates, these systems tend to be under-utilized.

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